

# Exploring star formation using the filaments in the Sloan Digital Sky Survey Data Release Five (SDSS DR5)

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## ABSTRACT

We have quantified the average filamentarity of the galaxy distribution in seven nearly two dimensional strips from the SDSS DR5 using a volume limited sample in the absolute magnitude range  $-21 \leq M_r \leq -20$ . The average filamentarity of star forming (SF) galaxies, which are predominantly blue, is found to be more than that of other galaxies which are predominantly red. This difference is possibly an outcome of the fact that blue galaxies have a more filamentary distribution. Comparing the SF galaxies with only the blue other galaxies, we find that the two show nearly equal filamentarity. Separately analyzing the galaxies with high star formation rates (SFR) and low SFR, we find that the latter has a more filamentary distribution. We interpret this in terms of two effects (1.) A correlation between the SFR and individual galaxy properties like luminosity with the high SFR galaxies being more luminous (2.) A relation between the SFR and environmental effects like the density with the high SFR galaxies preferentially occurring in high density regions. These two effects are possibly not independent and are operating simultaneously. We do not find any difference in the filamentarity of SF galaxies and AGNs.

**Key words:** methods: numerical - galaxies: statistics - cosmology: theory - cosmology: large scale structure of universe

## INTRODUCTION

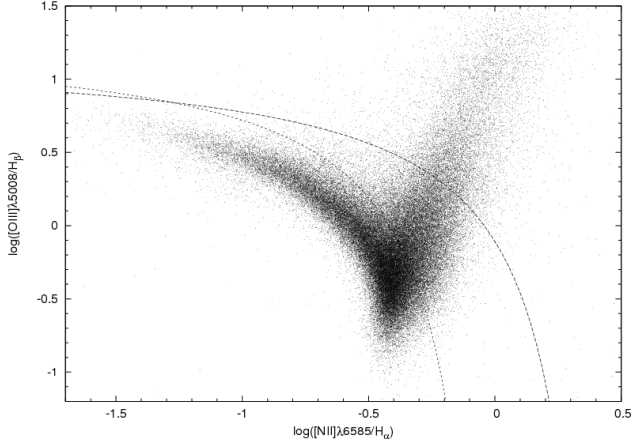
Determining the factors that govern star formation in a galaxy is an important issue which is expected to shed light on our understanding of how galaxies are formed. It is believed that there are several interlinked factors like turbulence, magnetic fields, cosmic rays, stellar winds, supernova explosions, etc. functioning in a galaxy's interstellar medium (ISM) which together regulate star formation in the galaxy (see Larson 2003, McKee & Ostriker 2007 for recent reviews). There is now mounting evidence that in addition to these factors operating inside a galaxy, its star formation is also influenced by external factors. It is quite clear that interactions between galaxies (e.g. Byrd & Valtonen 1990, Moore et al. 1999) and the interactions of a galaxy with the external ambient medium (e.g. Gunn & Gott 1972, Zabludoff et al. 1996, Porter & Raychaudhury 2007) can trigger star formation. There is also observational evidence that star formation is suppressed in regions where the galaxy density is high (Lewis et al. 2002; Gómez et al. 2003; Balogh et al. 2004). This is possibly related to the fact that

other galaxy properties like luminosity (e.g. Einasto et al. 2003, Einasto et al. 2005, Park et al. 2007), colour (e.g. Hogg et al. 2003, Blanton et al. 2003) and morphology (e.g. Dressler 1980, Goto et al. 2003) also exhibit environmental dependence.

The analysis of filamentary patterns in the galaxy distribution has a long history dating back to a few papers in the late-seventies and mid-eighties by Joeveer et al. (1978), Einasto et al. (1980), Zel'dovich, Einasto & Shandarin (1982), Shandarin & Zeldovich (1983) and Einasto et al. (1984). Filaments are the most striking visible patterns in the galaxy distribution (e.g. Geller & Huchra 1989, Shectman et al. 1996, Shandarin & Yess 1998, Bharadwaj et al. 2000, Müller et al. 2000, Basilakos, Plionis, & Rowan-Robinson 2001, Doroshkevich et al. 2004, Pimblett, Drinkwater & Hawkrigg 2004). The filamentarity is found to be statistically significant up to length-scales  $80 h^{-1} \text{Mpc}$  and not beyond (Bharadwaj, Bhavsar & Sheth 2004; Pandey & Bharadwaj 2005). Our earlier work (Pandey & Bharadwaj 2006, hereafter Paper A) shows the degree of filamentarity to depend on physical properties like the luminosity, colour and morphology of the galaxies. In the present work we investigate the relation between

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**Figure 1.** BPT diagnostic diagram showing the ratios  $[OIII]/H_\beta$  and  $[NII]/H_\alpha$  for all galaxies with  $I_\lambda/\sigma_{I_\lambda} > 2$ . The theoretical curve separating SF and AGNs (upper-dashed, Kewley et al. 2001) and the empirical curve (lower-dotted, Kauffmann et al. 2003) are shown.

the filamentarity observed in the galaxy distribution and ongoing star formation activity in the galaxies.

A brief outline of our paper follows. Section 2 describes the data and method of analysis, our results and conclusions are presented in Section 3. We have used a  $\Lambda$ CDM cosmological model with  $\Omega_{m0} = 0.3$ ,  $\Omega_{\Lambda 0} = 0.7$  and  $h = 1$  throughout.

## DATA AND METHOD OF ANALYSIS

The Sloan Digital Sky Survey (SDSS, York et al. 2000) is a five-passband (u,g,r,i,z) imaging and spectroscopic survey of the Northern Galactic hemisphere to a limiting Petrosian r band magnitude  $r < 17.77$ . Our analysis is limited to seven thin strips on the sky drawn from the SDSS DR5 (Adelman-McCarthy et al. 2006), each spanning  $90^\circ$  in  $\lambda$  and  $2^\circ$  in  $\eta$ . Here  $\lambda$  and  $\eta$  are survey co-ordinates defined in Stoughton et al. (2002). These strips are identical in sky-coverage as the ones used in Paper A and are shown in Figure 1 of that paper. Only galaxies with extinction corrected Petrosian r band magnitude in the range  $14.5 \leq m_r \leq 17.77$  were used. Volume limited samples are constructed in the same way as discussed in Paper A. The samples cover r-band absolute magnitude range  $-21 \leq M_r \leq -20$  and redshift range  $0.043657 \leq z \leq 0.114635$  which correspond to  $130 h^{-1} \text{Mpc}$  to  $335 h^{-1} \text{Mpc}$  comoving in the radial direction. Finally we have 17225 galaxies distributed in seven strips.

Seven emission lines ( $H_\alpha(6565\text{\AA})$ ,  $H_\beta(4863\text{\AA})$ ,  $OI(6302\text{\AA})$ ,  $OII(3727\text{\AA})$ ,  $OIII(5008\text{\AA})$ ,  $NII(6585\text{\AA})$ ,  $SII(6718\text{\AA})$ ) are required to classify a galaxy as either star forming (SF) or AGN. Only the galaxies having all these seven emission lines with  $I_\lambda/\sigma_{I_\lambda} > 2$  for all the lines are considered for classification as SF or AGN, galaxies which fail to meet this criteria are referred to as Other galaxies. Here  $I_\lambda$  is the emission line flux and  $\sigma_{I_\lambda}$  is its uncertainty. We have further classified the Other galaxies as either red ( $u-r > 2.22$ ) or blue using the criteria proposed by Strateva et al. (2001). This color selection criteria ensures that the red galaxies

are ‘ellipticals’ with 90% completeness. Most of the galaxies ( $\sim 80\%$ ) classified as Other are found to be red galaxies.

Both the SF galaxies and AGNs show strong  $H_\alpha$  emission. To differentiate between them we use the BPT diagram (Baldwin et al. 1981) where the logarithm of the ratio’s of  $[OIII]/H_\beta$  and  $[NII]/H_\alpha$  are plotted (Figure 1). We used together the demarcation curve provided by Kauffmann et al. (2003),  $\log(\frac{[OIII]}{H_\beta}) > 0.61/(\log(\frac{[NII]}{H_\alpha}) - 0.05) + 1.3$  and the theoretical separation curve  $\log(\frac{[OIII]}{H_\beta}) > 0.61/(\log(\frac{[NII]}{H_\alpha}) - 0.47) + 1.19$  provided by Kewley et al. (2001). Galaxies which lie below both these two curves are classified as SF whereas those which lie above both the curves are classified as AGNs. Galaxies living in the intermediate region of these two curves are discarded from further analysis.

Table I. gives a detailed break-up of the composition of the seven slices. When comparing the filamentarity of two different classes of galaxies it is necessary that the galaxy number density be the same for both the classes (Paper A). We have ensured this by culling the class of galaxies which have a larger number density.

The  $H_\alpha$  line was used to determine the star formation rate (SFR) of the SF galaxies in units of  $(M_\odot \text{yr}^{-1})$  using the relation given by Hopkins et al. (2003)

$$SFR_{H_\alpha}(M_\odot \text{yr}^{-1}) = 4\pi D_l^2 S_{H_\alpha} \frac{10^{-0.4(r_{\text{petro}} - r_{\text{fiber}})}}{1.27 \times 10^{34}} \left( \frac{S_{H_\alpha}/S_{H_\beta}}{2.86} \right)^{2.114}$$

where  $D_l$  is the luminosity distance,  $S_{H_\alpha}$  and  $S_{H_\beta}$  are the stellar absorption corrected  $H_\alpha$  and  $H_\beta$  fluxes respectively and  $r_{\text{petro}}$  and  $r_{\text{fiber}}$  are r-band Petrosian and fiber magnitudes respectively. The reader is referred to Kennicutt (1998) for various other definitions of the SFR. The SF galaxies are further classified as either high SFR or low SFR galaxies using the criteria  $SFR > 2.7 M_\odot \text{yr}^{-1}$  which has been chosen so that the number density of high and low SFR galaxies are nearly the same.

All the strips that we have analyzed are nearly two dimensional. The strips were all collapsed along the thickness (the smallest dimension) to produce 2D galaxy distributions. We use the 2D ‘Shapefinder’ statistic (Bharadwaj et al. 2000) to quantify the average filamentarity of the patterns in the resulting galaxy distribution. A detailed discussion is presented in Paper A, and we present only the salient features here. The reader is referred to Sahni, Sathyaprakash, & Shandarin (1998) for a discussion of Shapefinders in three dimensions.

The galaxy distribution is represented as a set of 1s on a 2-D rectangular grid of spacing  $1 h^{-1} \text{Mpc} \times 1 h^{-1} \text{Mpc}$ , empty cells are assigned a value 0. We identify connected cells with a value 1 as clusters using the ‘Friends-of-Friend’ (FOF) algorithm. The filamentarity of each cluster is quantified using the Shapefinder  $\mathcal{F}$  defined as

$$\mathcal{F} = \frac{(P^2 - 16S)}{(P - 4l)^2} \quad (1)$$

where  $P$  and  $S$  are respectively the perimeter and the area of the cluster, and  $l$  is the grid spacing. The Shapefinder  $\mathcal{F}$  has values 0 and 1 for a square and filament respectively, and it assumes intermediate values as a square is deformed to a filament. We use the average filamentarity

**Table 1.** The definition and composition of the seven strips analyzed here.

Strip	Lambda Range	Eta Range	Total Number of galaxies(All)	Star forming	AGN	Other	Other Blue
Strip 1	$-50 \leq \lambda \leq 40$	$9 \leq \eta \leq 11$	2922	774	189	1959	333
Strip 2	$-50 \leq \lambda \leq 40$	$11 \leq \eta \leq 13$	2470	655	156	1659	327
Strip 3	$-60 \leq \lambda \leq 30$	$13 \leq \eta \leq 15$	2296	649	153	1494	315
Strip 4	$-60 \leq \lambda \leq 30$	$15 \leq \eta \leq 17$	2300	644	133	1523	266
Strip 5	$-50 \leq \lambda \leq 40$	$21.5 \leq \eta \leq 23.5$	2454	702	152	1600	283
Strip 6	$-50 \leq \lambda \leq 40$	$24 \leq \eta \leq 26$	2541	671	181	1689	325
Strip 7	$-50 \leq \lambda \leq 40$	$26 \leq \eta \leq 28$	2242	617	173	1452	284

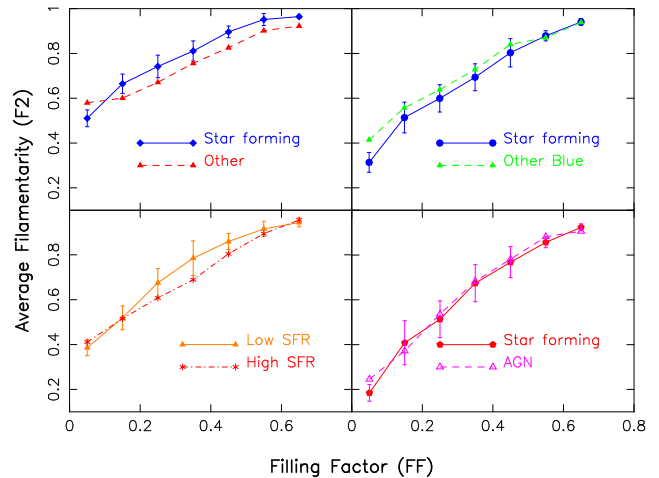
$$F_2 = \frac{\sum_i \mathcal{S}_i^2 \mathcal{F}_i}{\sum_i \mathcal{S}_i^2}. \quad (2)$$

to assess the overall filamentarity of the clusters in the galaxy distribution.

The distribution of 1s corresponding to the galaxies is sparse. Only  $\sim 1\%$  of the cells contain galaxies and there are very few filled cells which are interconnected. As a consequence FOF fails to identify the large coherent structures which corresponds to filaments in the galaxy distribution. We overcome this by successively coarse-graining the galaxy distribution. In each iteration of coarse-graining all the empty cells adjacent to a filled cell are assigned a value 1. This causes clusters to grow, first because of the growth of individual filled cells, and then by the merger of adjacent clusters as they overlap. Coherent structures extending across progressively larger length-scales are identified in consecutive iterations of coarse-graining. Finally a transition from many individual structures to an interconnected network is found to occur at a filling factor  $0.5 - 0.6$  (Pandey & Bharadwaj 2006).

So as not to restrict our analysis to an arbitrarily chosen level of coarse-graining, we study the average filamentarity after each iteration of coarse-graining. The filling factor  $FF$  quantifies the fraction of cells that are filled and its value increases from  $\sim 0.01$  and approaches 1 as the coarse-graining proceeds. We study the average filamentarity  $F_2$  as a function of the filling factor  $FF$  (Figure 2) as a quantitative measure of the filamentarity at different levels of coarse-graining. The values of  $FF$  corresponding to a particular level of coarse-graining shows a slight variation from strip to strip. In order to combine and compare the results from different strips, for each strip we have interpolated  $F_2$  to 7 values of  $FF$  at an uniform spacing of 0.1 over the interval 0.05 to 0.65. Coarse-graining beyond  $FF \sim 0.65$  washes away the filaments and hence we do not include this range for our analysis.

Our method of analysis is similar to the Friend-of-Friends method with varying linking length and also the density field (DF) method with a fixed smoothing length and varying threshold density (Einasto et al. 2007c). All these methods identify density enhancements in the cosmic web. With increasing lengthscale we progress from clusters ( $\sim 1 - 10$  Mpc) to superclusters ( $\sim 10 - 100$  Mpc) and finally an infinite interconnected network, the cosmic web. Often individual one dimensional structures are identified as filaments using a variety of criteria, for example a chain of galaxies connecting two adjacent clusters (Pimblett, Drinkwater & Hawkrigg 2004; Stoica et al.

**Figure 2.** Average Filamentarity as a function of Filling Factor comparing the different classes of galaxies indicated in the panels.

2007). Instead of focusing on the properties of individual structures, we quantify the overall filamentarity of the entire galaxy distribution. This is done over a range of filling factors. Figure 9 of Paper A shows that the average length of the structures identified by our method is  $\sim 10$  Mpc at  $FF \leq 0.1$  corresponding to galaxy clusters,  $\leq 100$  Mpc for  $FF \leq 0.4$  corresponding to superclusters and the average length is  $> 100$  Mpc for  $0.5 \leq FF \leq 0.6$  where we have the percolation transition. We note that the percolation threshold is  $FF = 0.12$  in the DF method (Einasto et al. 2005, 2006, 2007c) indicating that the structures identified by our method are inherently thicker enclosing larger empty regions relative to the DF method. Despite this, it is justified to refer to these structures as filaments because the average filamentarity  $F_2$  of these structures is quite high (Figure 2) for a large range of the filling factor  $FF$ .

## RESULTS AND CONCLUSIONS

We first compare the average filamentarity of the star forming galaxies with that of the Other galaxies. For both classes of galaxies we use the results from the seven different strips to compute the mean and variance of the average filamentarity  $F_2$  at uniformly chosen values of the filling factor  $FF$ . The results are shown in the top left panel of Figure 2. We find that the SF galaxies have a higher  $F_2$  compared to the Other galaxies at all values of  $FF$  except at the smallest values  $FF < 0.1$  where the Other galaxies have a larger  $F_2$ .

At each value of  $FF$  we use the Student's t-test to determine whether the differences in  $F_2$  between the SF and Other galaxies is statistically significant or not. For each class of galaxies we have seven strips which we use to calculate the mean and variance of  $F_2$ . We use the Student's t-test to test the null hypothesis that the mean  $F_2$  is the same for the two classes of galaxies. The variance in  $F_2$  is similar for the SF and the Other galaxies, and we use

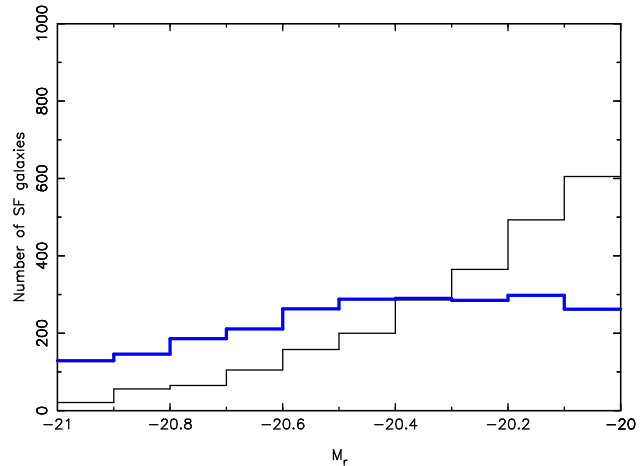
$$s_D = \sqrt{\frac{\sum_{i \in A} (x_i - \bar{x}_A)^2 + \sum_{i \in B} (x_i - \bar{x}_B)^2}{N_A + N_B - 2}} \left( \frac{1}{N_A} + \frac{1}{N_B} \right)$$

to estimate the standard error for the difference in the means. Here A and B refer to the SF and Other galaxies respectively,  $\bar{x}_A$  and  $\bar{x}_B$  refer to the mean  $F_2$  for the respective class of galaxies and  $N_A = N_B = 7$  respectively refer to the number of data points (different slices) for each class of galaxies. We use  $t = \frac{\bar{x}_A - \bar{x}_B}{s_D}$  to estimate the significance of the differences in the means. This is expected to follow a Student's t-distribution with 12 degrees of freedom. We accept the difference in the means as being statistically significant if the probability of its occurring by chance is less than 5%. Here we find that the difference in the mean average filamentarity between the SF and Other galaxies is statistically significant at all values of  $FF$ .

In an earlier work (Pandey & Bharadwaj 2006) we have studied the colour and morphology dependence of  $F_2$ . We find that the blue galaxies have a larger value of  $F_2$  at nearly the entire range of  $FF$  except at the smallest values ( $FF \leq 0.2$ ) where the red galaxies have a larger  $F_2$ . A similar behaviour was also seen when the spirals were compared with the elliptical galaxies. It was found that at large  $FF$  the spirals have a larger  $F_2$  as compared to ellipticals, and the behaviour is reversed at ( $FF \leq 0.25$ ). Most of the SF galaxies are blue while the Other galaxies are a mixture of blue (spiral) and red (elliptical) galaxies. As noted earlier, the Other galaxies are predominantly red ellipticals ( $\sim 80\%$ ). To test if the observed difference in the filamentarity between the SF and Other galaxies is a consequence of the fact that the SF galaxies are predominantly blue galaxies whereas the Other galaxies are predominantly red, we have separately compared the SF galaxies with blue galaxies drawn from the Other galaxies. The results are shown in the top right panel of Figure 2. We find that the blue galaxies drawn from the Other galaxies have a higher  $F_2$  than the SF galaxies for the entire  $FF$  range, though the difference is statistically significant at only the smallest  $FF$  value. The error-bars for the comparison of SF and blue Other galaxies are relatively larger than those for the comparison of SF and the entire sample of Other galaxies. The large error-bars do not permit us to rule out the possibility that the excess filamentarity of the SF galaxies relative to the Other galaxies is a reflection of the differences in the filamentarity of red and blue galaxies.

We next compare the filamentarity of SF galaxies with that of AGNs. The results are shown in the bottom right panel of Figure 2. We find no statistically significant difference in the filamentarity of SF galaxies and AGNs except at the lowest value  $FF = 0.05$  where the AGNs have a larger filamentarity compared to the SF galaxies.

Finally we divide the SF galaxies into two classes with equal number of galaxies based on their star formation rates (SFR) and compare the filamentarity of the galaxies with low SFR ( $< 2.7 M_\odot \text{yr}^{-1}$ ) with those with high SFR. The



**Figure 3.** Absolute magnitude distribution of high SFR (thick blue) and low SFR (thin black) galaxies.

results are shown in the bottom left panel of Figure 2. We find that there is a statistically significant difference over the range  $0.25 \leq FF \leq 0.45$  corresponding to superclusters. The low SFR galaxies show a higher filamentarity compared to the high SFR galaxies. The filamentarity of high and low SFR galaxies do not show any statistically significant differences at low and high  $FF$ .

Earlier works (Pandey & Bharadwaj 2005, 2006) show that the low luminosity galaxies have a higher filamentarity compared to the high luminosity galaxies. (Figure 7, Paper A). This is very similar to the drop in the filamentarity of high SFR galaxies compared to the low SFR ones. A possible explanation for the difference in filamentarity observed between high SFR and low SFR galaxies is to assume that the SFR is related to luminosity, with the more luminous galaxies having a higher SFR. To test if there actually is a relation between the SFR and the luminosity, we have separately considered the luminosity (absolute magnitude) distribution of the galaxies in the low SFR and high SFR classes (Figure 3). We find that there is a relatively larger number of low luminosity galaxies in the low SFR class as compared to the high SFR class. Similarly there is a larger number of high luminosity galaxies in the high SFR class in comparison with the low SFR class.

Brinchmann et al. (2004) have used a large sample of star forming galaxies drawn from the SDSS to study how the SFR depends on various physical parameters of the individual galaxies. In Figure 17 of their paper they show evidence for a strong correlation between the stellar mass and the SFR. Over a large range of stellar masses  $6 < \log(M_*/M_\odot) < 10$  they find that the mean SFR increases with  $M_*$ . The correlation breaks down at  $\log(M_*/M_\odot) \gtrsim 10$ . Further, they find that the strong correlation between  $M_*$  and the SFR is a recurring theme throughout their analysis.

Environmental effects are another important factor which could be responsible for the high SFR galaxies having a lower filamentarity. Our earlier works using N-body simulations (Bharadwaj & Pandey 2004; Pandey & Bharadwaj 2007) show that the filamentarity depends on the bias. The filamentarity falls if the galaxies have a high bias *ie* the galaxies preferentially inhabit high density regions. It is thus possible to explain our findings if we assume that the high

SFR galaxies preferentially inhabit denser regions compared to the low SFR ones.

In summary we have identified two possible explanations for the fact that the high SFR galaxies have a less filamentary distribution than the low SFR ones: (1.) A correlation between the SFR and individual galaxy properties like luminosity (2.) A relation between the SFR and environmental effects like the density. Possibly both of these are interconnected and are simultaneously at play. It is interesting to discuss these two possibilities in the light of other related findings. It is well known that the more luminous galaxies preferentially inhabit denser regions (e.g. Einasto & Einasto 1987, Einasto et al. 2003, Einasto et al. 2006, Park et al. 2007,) and exhibit stronger clustering strength compared to the fainter ones (e.g. Hamilton 1988, Davis et al. 1988, White, Tully & Davis 1988, Park, Vogeley, Geller & Huchra 1994, Loveday et al. 1995, Guzzo et al. 1997, Norberg et al. 2001, Zehavi et al. 2005). This effect is quantified through a luminosity bias relation (Benoist et al. 1996; Norberg et al. 2001; Tegmark et al. 2004; Pandey & Bharadwaj 2007). Earlier studies of the environment dependence (Lewis et al. 2002; Gómez et al. 2003; Balogh et al. 2004) all show a suppression of star formation activity in high density regions. While these works all find a decrease in the fraction of SF galaxies within a distance of  $2 - 3$  virial radius from the center of clusters, the effect of density on the SFR distribution is not clear. Gómez et al. (2003) find that the SFR distribution is strongly shifted to lower values in high density environments, the effect being most pronounced for the strongest star forming galaxies whereas Balogh et al. (2004) find that the SFR distribution is independent of environment. Einasto et al. (2007a) find that the fraction of SF galaxies in rich groups/clusters in high density regions of rich supercluster is smaller than what is found in poor superclusters in the field. In their analysis superclusters are connected non-percolating systems with densities above a certain density threshold. Einasto et al. (2007b) also find that the more luminous and richer superclusters have a higher degree of filamentarity compared to the poor ones. Einasto (1991) and Einasto et al. (2007a) show that both the local and the global environment are possibly important in influencing morphological properties and star formation. Recently Lee & Li (2008) have studied the correlation between the large scale environment of galaxies and their physical properties in the SDSS and the 2Mass Redshift Survey. They find that the physical parameters related to the recent star formation history are linked to the shear of the large scale environment of galaxies. A study of star formation along the Pisces-Cetus Supercluster filaments (Porter & Raychaudhury 2007) finds that though the SFR and the fraction of SF galaxies declines steadily towards the cores of clusters, there is an increased SF activity in a narrow distance range around 1.5 to 2 times the virial radius of the cluster involved. A study of the environment and clustering properties of star-burst galaxies in the 2dFGRS (Owers et al. 2007) finds that a significant fraction of star-burst galaxies show morphological evidence for ongoing or recent tidal interaction or merger.

There appears to be no consensus on how star formation depends on the environment and some of the findings appears to be at odds with our results, we note that the as-

sociated length-scales are quite different. While the earlier studies probed groups and clusters of galaxies *ie.* length-scales less than a few Mpc, the structures identified by our method have lengths of the order of 100 Mpc/h and thickness of the order 5 Mpc/h (Figure 9, Paper A) for the range of  $FF$  where the difference in filamentarity is statistically significant. Our interpretation is consistent with the recent analysis by Shioya et al. (2007) who has shown that the high SF galaxies at  $z \approx 0.24$  are more strongly clustered than the low SF galaxies.

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